Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 75 (2015) 265 – 270

Energy Procedia

The 7th International Conference on Applied Energy – ICAE2015

Sliding Mode Control for Power Output maximization in a Wave Energy Systems

Oscar Barambones* and J.M. Gonzalez de Durana

Vitoria Engineering School, University of the Basque Country. Nieves cano 12. 01006 Vitoria, Spain

Abstract

Modern wave power generation plants are capable to work in variable speed operations. These wave power generation plants are provided with adjustable speed generators, like the double feed induction generator. One of the main advantages of adjustable speed generators is that they improve the system efficiency compared to fixed speed generators, because turbine speed can be adjusted as a function of the flow coefficient to maximize the output power. However these systems require a suitable speed controller in order to track the optimal turbine reference speed. In this work, a sliding mode control for variable speed wave power generation plants is proposed.

The stability analysis of the proposed controller is provided under disturbances and parameter uncertainties by using the Lyapunov stability theory. Finally simulated results show, on the one hand that the proposed controller provides high-performance dynamic characteristics, and on the other hand that this scheme is robust with respect to the uncertainties that usually appear in the real systems.

Keywords: *Robust control; Doubly Fed Induction Generator; Sliding mode control; Wave energy; Wells Turbine ;*

1. Introduction

Wave power is an abundant renewable source of electricity by converting the kinetic energy of the waves into electricity. Many renewable power-generation plants, like wind turbine systems and wave energy plants, incorporate a doubly fed induction generator (DFIG) to allow variable rotor speed operation [1], [2].

Traditionally the control of a DFIG are simplified by means of the vector or field control schemes and then using a cascaded PI current and power loops. However, as it is well known, the real system parameters always differ from those obtained from the data sheet used for PI tuning, so a fine tuning over the real system is always required to achieve an adequate performance, and the PI controllers may present a considerable lack of robustness depending on the tuning method employed [3].

* Corresponding author. Tel.: +34 945 013235; fax: +34 945 013270.
E-mail address: oscar.barambones@ehu.es.

Peer-review under responsibility of Applied Energy Innovation Institute
doi:10.1016/j.egypro.2015.07.332

Taking into account the previous considerations some kind of robust control scheme should be considered for this kind of systems in order to improve the controller performance under system uncertainties. In this sense, the sliding-mode control (SMC) initially developed by Utkin and successfully applied to diverse types of induction machine drives [4] can be a suitable choice. The SMC, allows to avoid the need of an exact knowledge of the system parameters and offers many desirable properties, such as good performance against unmodeled dynamics, insensitivity to parameter variations, and an excellent external disturbance rejection. Recently some SMC schemes has been proposed in order to extract the maximum power from the wind turbine system equipped with a DFIG [5].
This paper presents a SMC scheme in order to improve the power extraction in OWC wave energy generation plants equipped with a DFIG. The objective is to attain that the turbine speed tracks the optimum speed, that maximizes the power extraction from the Wells turbine, in spite of system uncertainties.

2. OWC Plant modeling

In this work the NEREIDA MOWC project is considered as a system that can be controlled using the proposed robust control design. NEREIDA MOWC is a project involving the integration of an OWC system with Wells turbines in the new rockfill breakwater at the harbor in Mutriku in the north coast of Spain.
In this system, the turbogenerator module is composed by two five-blade Wells turbines that turn together, connected to an air cooled DFIG. In this kind of induction machines, widely employed in diverse generation applications, the stator circuit is directly connected to the grid while the rotor winding is connected via slip rings to a variable frequency converter (VFC). In order to produce electrical active power at constant voltage and frequency to the utility grid, over a wide operation range (from subsynchronous to supersynchronous speed), the active power flow between the rotor circuit and the grid must be controlled both in magnitude and in direction. Therefore, the VFC consists of two four-quadrant IGBT PWM converters (rotor-side converter and grid-side converter) connected back-to-back by a dc-link capacitor [6].
The main advantage of this design is that the power electronic converters only need to handle a fraction about (25%-30%) of the nominal power so that the losses in the power converter are small compared to other kinds of designs, with the consequent cost reduction in the necessary electronics.

For this OWC wave power system, the Wells fixed-pitch turbines are considered. This kind of turbine has a robust and simple symmetrical blade design, which means that it always rotates in the same direction, regardless of the direction of the airflow through the turbine, so that no device is needed to rectify the airflow. The equations used for the modeling of the turbine are given by [8]:

$$dP = C_a\, k\, \frac{1}{a}[v_x^2 + (r\,w)^2] \tag{1}$$

$$T_t = C_t\, k\, r\, [v_x^2 + (r\,w)^2] \tag{2}$$

$$T_t = \frac{C_t\, r\, a}{C_a} dP \tag{3}$$

$$\phi = \frac{v_x}{rw} \tag{4}$$

where $dP(Pa)$ is the pressure drop across the turbine, C_a is the power coefficient, a is the area of turbine duct, $v_x(m/s)$ is the airflow speed, $r(m)$ is the turbine radius, $w(rad/s)$ is the turbine angular velocity, $T_t(Nm)$ is the torque generated by the Wells turbine, C_t is the torque coefficient, k(Kg m) is a turbine constant and ϕ is the flow coefficient.
The performance of the Wells turbine is limited by the onset of the stalling phenomenon on the turbine blades, because when the airflow velocity exceeds a critical value (that depends on the turbine rotational

speed), the Wells turbine efficiency drops drastically. Therefore, the maximum power that can be extracted by the Wells turbine is limited by its stalling behavior. A turbine blade stalls when the relative angle between the tangential speed of the turbine and the axial velocity of the input airflow exceeds a value about 14° [8].

When the stalling phenomenon occurs, the torque coefficient C_t drops drastically, and therefore the torque generated by the turbine is greatly reduced. Figure 1 shows the torque coefficient versus flow coefficient ($\phi = \frac{v_x}{rw}$) for a typical Wells turbine, even though it should be noted that the values for the turbine torque coefficient will depend on the design parameters of the Wells turbine.

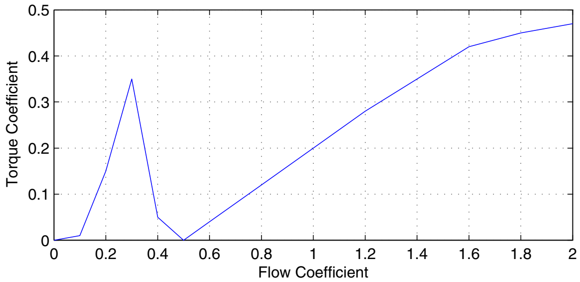

Figure 1: Torque Coefficient Flow coefficient

From figure 1, it may be observed that when the flow coefficient increases and approaches $\phi = 0.3$ (this value may change depending of the characteristic curve of each turbine), then appears the so-called stalling behaviour in the turbine. In this figure it can also be observed that the optimal value for the flow coefficient could be $\phi_{opt} = 0.29$, because at this point the maximum C_t value is obtained, avoiding the stalling behavior.

Then, the value for the optimal turbine speed command that generates the maximum wave power extraction is determined by:

$$w^* = \frac{v_x}{r \cdot \phi_{opt}} \tag{6}$$

3. Sliding Mode Controller design

In order to extract the maximum power from the sea, the shaft speed of the OWC turbogenerator must be controlled so that the flow coefficient ϕ remains bounded, yielding to a maximum stalling free torque coefficient C_t. The design of the SMC requires to take into account the dynamics of the turbogenerator module. The mechanical dynamic equation for the turbogenerator may be written as:

$$J\dot{w} + Bw = T_t - \gamma T_e \tag{7}$$

where J is the inertia moment B is the viscous friction coefficient, T_t is the torque generated in the turbine by the air flow produced by the waves, T_e is the the generator torque, w is the angular velocity of the turbine shaft and the gear ratio $\gamma = w_e/w$ is the relation between the angular velocity of the turbine shaft w and the angular velocity of the generator rotor w_e.

The electrical equations of the DFIG can be simplified using the field-oriented-control; that is, referring all expressions to the stator-flux reference frame. In the stator-flux oriented reference frame, the d-axis is aligned with the stator flux linkage vector ψ_s, and then, ψ_{ds}=ψ_s and ψ_{qs}=0. This yields the following value for the electromagnetic torque [6]:

$$T_e = -K_T i_{qr} \tag{8}$$

where K_T is a torque constant.

From equations (7) and (8), and taken into account the uncertainties the following dynamic equation may be written:

$$\dot{\mathrm{w}} = -(\mathrm{a} + \Delta\, \mathrm{a})\mathrm{w} + (\mathrm{f} + \Delta\, \mathrm{f}) - (\mathrm{b} + \Delta\, \mathrm{b})\mathrm{i}_{\mathrm{qs}} \tag{9}$$

where $\mathrm{a} = \frac{\mathrm{B}}{\mathrm{J}}$, $\mathrm{b} = \frac{\gamma \mathrm{K_T}}{\mathrm{J}}$, $\mathrm{f} = \frac{\mathrm{T_m}}{\mathrm{J}}$ and the terms Δ a, Δ b and Δ f represents the uncertainties of the terms a, b and f respectively.

Let us define the speed tracking error as follows:

$$\mathrm{e(t) = w(t) - w^*(t)} \tag{10}$$

where w^* is the turbine speed command that provides the maximum wave power extraction.

Taking the derivative of the previous equation with respect to time yields:

$$\dot{\mathrm{e}}(\mathrm{t}) = \dot{\mathrm{w}} - \dot{\mathrm{w}}^* = -\mathrm{a}\, \mathrm{e(t) + u(t) + d(t)} \tag{11}$$

where the signal $\mathrm{u(t)}$ collects the known terms:

$$\mathrm{u(t) = f(t) - b\, i_{qr}(t) - a\, w^*(t)} - \dot{\mathrm{w}}^*(\mathrm{t}) \tag{12}$$

and the signal $\mathrm{d(t)}$ contains the uncertainty terms:

$$\mathrm{d(t)} = -\Delta\, \mathrm{a\, w(t)} + \Delta\, \mathrm{f(t)} - \Delta\, \mathrm{b\ i_{qr}(t)} \tag{13}$$

To compensate the above system uncertainties an SMC scheme is proposed.

The sliding variable $\mathrm{S(t)}$ is defined as:

$$\mathrm{S(t) = e(t)} + \int_0^{\mathrm{t}} (\mathrm{k + a})\mathrm{e}(\tau)\, \mathrm{d}\tau \tag{14}$$

where k is a positive constant gain.

Finally, sliding mode speed controller is designed as:

$$\mathrm{u(t)} = -\mathrm{k\, e(t)} - \beta\, \mathrm{sgn\,(S)} \tag{15}$$

where β is the switching gain that should be greater that the system uncertainties ($\beta \geq |\mathrm{d(t)}|$), S is the sliding variable and sgn $(\cdot)$ is the signum function.

The stability of this system can be demonstrated using the following Lyapunov function: $\mathrm{V(t)} = \frac{1}{2}\mathrm{S(t)S(t)}$, whose time derivative is:

$$\begin{aligned} \dot{\mathrm{V}}(\mathrm{t}) &= \mathrm{S(t)}\dot{\mathrm{S}}(\mathrm{t}) \\ &= \mathrm{S} \cdot [\dot{\mathrm{e}} + (\mathrm{k+a})\mathrm{e}] = \mathrm{S} \cdot [(-\mathrm{a\, e + u + d}) + (\mathrm{k\, e + a\, e})] \\ &= \mathrm{S} \cdot [-\mathrm{k\, e} - \beta\, \mathrm{sgn\,(S) + d + k\, e}] = \mathrm{S} \cdot [\mathrm{d} - \beta\, \mathrm{sgn\,(S)}] \\ &\leq -(\beta - |\mathrm{d}|)|\mathrm{S}| \leq 0 \end{aligned} \tag{16}$$

Using the Lyapunov's direct method, since $\mathrm{V(t)}$ is clearly positive-definite, $\dot{\mathrm{V}}(\mathrm{t})$ is negative definite and $\mathrm{V(t)}$ tends to infinity as $\mathrm{S(t)}$ tends to infinity, then the equilibrium at the origin $\mathrm{S(t) = 0}$ is globally asymptotically stable. Therefore $\mathrm{S(t)}$ tends to zero as the time tends to infinity.

When the sliding mode occurs on the sliding surface, then $\mathrm{S(t)} = \dot{\mathrm{S}}(\mathrm{t}) = 0$, and therefore the dynamic behavior of the tracking problem (11) is equivalently governed by the following equation:

$$\dot{\mathrm{S}}(\mathrm{t}) = 0 \quad \Rightarrow \quad \dot{\mathrm{e}}(\mathrm{t}) = -(\mathrm{k+a})\mathrm{e(t)} \tag{17}$$

Then, the tracking error $\mathrm{e(t)}$ converges to zero exponentially.

Finally, the torque current command, $i_{qr}^*(t)$, can be obtained from equations (12) and (15):

$$i_{qr}^*(t) = \frac{1}{b}[k\, e + \beta\, \mathrm{sgn}\,(S) - a\, w^* - \dot{w}^* + f] \tag{18}$$

Therefore, the proposed sliding mode control resolves the turbine speed tracking problem, for a wave power generation plant that includes a DFIG, in the presence of system uncertainties, and let us obtain the maximum wave power extraction by tracking the turbine speed reference value that gives the optimum flow coefficient for the Wells turbine.

4. Simulation results

In this section the speed regulation performance for the turbogenerator using the proposed sliding mode field oriented control scheme under system uncertainties is studied. The simulations are carried out using the Matlab/Simulink software and the SimPowerSystems library [9]. The objective of this regulation is to maximize the wave power extraction, in order to obtain the maximum electrical power. In this sense, the turbine speed must follows the optimal turbine speed command that produces the maximum mechanical power.

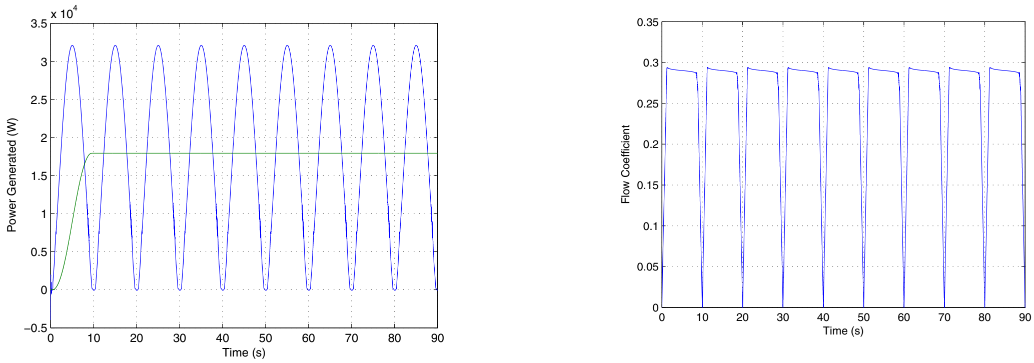

Fig. 2. Simulation results for the SMC control.

In the experimental validation it is assumed that there is an uncertainty of 20% in the system parameters that will be overcome by the proposed adaptive sliding mode control. In the example the values for the controller parameters are: $k = 1.56$ and $\beta = 0.37$. These values are experimentally tuned taking into account the influence of this parameters in the controller performance. In the selection of this control parameters the following rules must be taken into account. An increase in the parameter k gives an increase in the speed error convergence but this also increases the value of the control signal in the initial estate, when the error is high, which is undesirable in real applications. On the other hand, an increase in the parameter β increases the robustness but also can increase the control activity, which is not desirable.
In this simulation example an scenario where the waves produce a typical variation in the pressure drop given by $dP = |10000 \sin(0.1\pi t)|$ (Pa) is considered.
Figure 2 shows the electrical power generated, whose average value is $17.9\ kW$, and the flow coefficient for the SMC case. In this figure it can be observed that the generator speed regulation improves the flow coefficient values in order to optimize the mechanical power generation. Moreover, the proposed speed regulation also avoids the stalling behavior in the Wells turbine because the flow coefficient is maintained below the critical value $\phi = 0.3$.

Figure 3 shows the electrical power generated whose average value is 12.9 kW. Unlike the previous SMC controlled case, the undesirable stalling behaviour, that produces a power loss, can be observed in this figure. In this figure it can be observed that the flow coefficient exceeds the critical value $\phi = 0.3$ and therefore the stalling behavior appears in the dynamics of the Wells turbine because the flow coefficient is not optimized in order to increment the mechanical power generation.
Therefore, comparing Figures 2 and 3 it can be observed that the electrical power generated by a OWC system can be improved in two ways by means of the generator speed control. On the one hand the speed regulation improves the OWC system performance providing an optimum flow coefficient value for the Wells turbine that produces the maximum wave energy extraction. On the other hand the speed regulation can also be used to avoid the stalling behavior in the Wells turbine dynamics, because the flow coefficient can be maintained below the critical value $\phi = 0.3$.

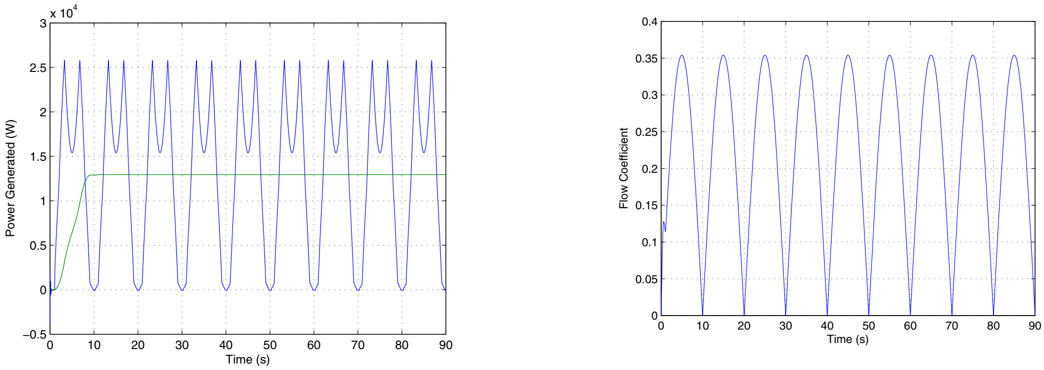

Fig. 3. Simulation results for the uncontrolled case

5. Conclusions

In this paper an adaptive SMC scheme for OWC wave power generation plants is proposed. Due to the nature of the SMC, this control is robust under uncertainties caused by parametrical errors or system disturbances. The closed-loop stability of the presented design has been proved through the Lyapunov stability theory, and the controller has been successfully validated by means of simulation examples. As a result, it can be concluded that the proposed adaptive SMC strategy improves the wave power extraction by means of the turbine speed control in order to obtain the optimum value for the flow coefficient. This optimum value for the flow coefficient provides the maximum power extraction for a given Wells turbine. Moreover, the proposed robust controller provides a good dynamic response, which is insensitive to parameter uncertainties and to disturbances in the system.

Acknowledgements

The authors are very grateful to the Basque Government by the support of this work through the project S-PE13UN039 and to the UPV/EHU by its support through the projects GIU13/41 and UFI11/07.

References

[1] M. Alberdi, M. Amundarain, F. J. Maseda and O. Barambones, Stalling behaviour improvement by appropriately choosing the rotor resistance value in Wave Power Generation Plants, in Proc. IEEE Int. Conf. on Clean Electrical Power 2009, pp. 64-67.
[2] M.S. Lagoun, S. Nadjem, A. Benalia and M.E.H. Benbouzid, Predictive Power Control of Doubly-Fed Induction Generator for Wave Energy Conveters, in Proc. of Int. Symp. on Environment-Friendly Energies and Applications 2012, pp. 312-317.
[3] K.J. Astrom and T. Hagglund, "The future of PID control",Control Engineering Practice, vol.9, no. 11, Nov. 2001
[4] Barambones, O., Alkorta P. Gonzlez de Durana J. M., A real-time estimation and control scheme for induction motors based on sliding mode theory, Journal of the Franklin Institute, vol. 351, pp. 4251-4270. 2014
[5] O. Barambones, "Sliding Mode Control Strategy for Wind Turbine Power Maximization", Energies, vol. 5, no. 7, pp. 2310-2330. 2012.
[6] R. Pena, J. C. Clare, and G. M. Asher, Doubly fed induction generator using back-to-back PWM converters and its application to variable-speed wind-energy generation, Proc. Inst. Elect. Eng.Elect. Power Appl., vol. 143, no. 3, pp. 231-241, May 1996.
[7] A.J. Garrido, I. Garrido, M. Amundarain, M. Alberdi, O. Barambones and J.A. Romero, "Robust Control of Oscillating Water Column (OWC) Devices: Power Generation Improvement", Proceedings of OCEANS'13 MTS/IEEE., September 2013.
[8] V. Jayashankar, K. Udayakumar B.Karthikeyan, K. Manivannan, N. Venkatraman and S. Rangaprasad, Maximizing Power Output From A Wave Energy Plant, in Proc. IEEE Power Eng. Soc. Winter Meeting 2000, vol. 3, pp. 1796-1801.
[9] SimPowerSystems 5. Users Guide, The MathWork